

A STUDY ON HEAT TREATMENT OF CARBURIZING CARBON STEEL

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I certify that the project entitled “*A study on heat treatment of carburizing carbon steel*” is written by *Mohd Marhan bin Asari*. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I here with recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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ABSTRACT

The main purpose of this study is to study the effect of heat treatment of carburizing carbon steel by using three parameters (carburizing hour, carburizing temperature, and quenching medium). This study was conducted using a furnace. This process is carried out at temperatures from 850°C to 950°C (1123 – 1223K) for three various duration time which are 8, 10 and 12 hours. From the experiment, the thickness of carbon layer varied according to the parameters that been used. For carburizing temperature at 950°C, the thickness of carbon layer was between 40µm to 80µm for oil as quenching medium, 60µm to 100µm for water as quenching medium and 20µm to 60µm for air as quenching medium. This experiment also been conducted for different carburizing temperature but with one quenching medium which is oil. The thickness of carbon layer was between 20µm to 60µm for 850°C, 30µm to 70µm for 900°C and 40µm to 80µm for 950°C. For carburizing temperature at 950°C, surface hardness values of carburized specimens were between 185.9 HV and 386.2 HV for oil as quenching medium, 234.7 HV and 398.4 HV for water as quenching medium and 120.7 HV and 241.5 HV for air as quenching medium. For different carburizing temperature, surface hardness values of carburized specimens were between 149 HV and 323.4 HV for 850°C, 166.4 HV and 345.9 HV for 900°C and 185.9 HV and 368.2 HV for 950°C. Activation energy was determined by 47.34 kJ/mol. The lower value of activation energy means less energy required for carbon atoms to diffuse into carbon steel, thus provide a more effective and efficient process.

ABSTRAK

Tujuan utama kajian ini adalah untuk mempelajari kesan-kesan rawatan haba terhadap penyusukkarbonan besi karbon dengan menggunakan tiga pembolehubah (jam penyusukkarbonan, suhu karburasi dan agen penyejukan). Kajian ini dijalankan dengan menggunakan kebuk pembakaran. Proses ini dilakukan pada suhu 850°C sehingga 950°C (1123 – 1223K) untuk tiga masa berbeza iaitu 8,10 dan 12 jam. Daripada kajian ini, ketebalan lapisan karbon berubah-ubah mengikut pembolehubah yang digunakan. Bagi penyusukkarbonan pada suhu 950°C, ketebalan lapisan karbon adalah diantara 40µm sehingga 80µm bagi minyak sebagai agen penyejukan, 60µm sehingga 100µm bagi air sebagai agen penyejukan dan 20µm sehingga 60µm bagi udara sebagai agen penyejukan. Kajian ini juga dilakukan untuk suhu penyusukkarbonan yang berbeza tetapi dengan hanya menggunakan satu agen penyejukan iaitu minyak. Ketebalan lapisan karbon adalah diantara 20µm sehingga 60µm bagi 850°C, 30µm sehingga 70µm bagi 900°C dan 40µm sehingga 80µm bagi 950°C. Bagi suhu penyusukkarbonan pada 950°C, nilai kekerasan lapisan bahan yang disusukkarbonan adalah diantara 185.9 HV dan 386.2 HV bagi minyak sebagai agen penyejukan, 234.7 HV dan 398.4 HV bagi air sebagai agen penyejukan dan 120.7 HV dan 241.5 HV bagi udara sebagai agen penyejukan. Bagi suhu penyusukkarbonan yang berbeza, nilai kekerasan lapisan bahan yang disusukkarbonan adalah diantara 149 HV dan 323.4 HV bagi 850°C, 166.4 HV dan 345.9 HV bagi 900°C and 185.9 HV dan 368.2 HV bagi 950°C. Tenaga pengaktifan diperkirakan iaitu 47.34 kJ/mol. Semakin rendah nilai tenaga pengaktifan bermaksud kurang tenaga diperlukan bagi atom karbon masuk ke dalam besi karbon lalu menyediakan satu proses yang efektif dan cekap.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Generally, heat treatment processes apply primarily to steels. After a component has been produced, it may still not have acceptable surface properties. There are few reasons why the surface properties may need altering such as improving wear, corrosion and fatigue resistance, and changing the aesthetic appearance. There are various ways these aims can be achieved.

Heat treatment is a method used to alter the physical and sometimes chemical properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material.

Case hardening is a process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness (Prabudev, 1988).

1.2 PROBLEM STATEMENT

Optimum structural material is a great concern in manufacturing environments, where demands for high performance in mechanical properties such as hardness.

The influence of heat treatment on the mechanical properties of the carbon steel is studied. Choosing the best carburizing time, quenching medium and carburizing temperature is the main priority in this research because with the suitable carburizing time, quenching medium and carburizing temperature, it can give precise results in mechanical properties such as hardness.

1.3 PROJECT BACKGROUND

In order to make strong structural material, the material for this research is low Carbon Steels (0.4 wt. %). In general, carburizing process increases the grains size due to permanence for a long time in the austenite region of the phase diagram, and makes necessary a posterior heat treatment to refine the grains. The process that generally involved in heat treatment is quenching. The material is heated to certain temperatures and then rapidly cooled (quenched) in water, oil, and air. This results in martensite structure which is a form of steel that possesses super-saturated carbon content in a deformed body-centered cubic (BCC) crystalline structure, properly termed body-centered tetragonal (BCT), with much internal stress. Thus, quenched steel is extremely hard but brittle, usually too brittle for practical purposes. These internal stresses cause stress cracks on the surface (Prabudev, 1988).

The increasing in the mechanical properties because of the modified microstructures confirmed the efficiency of the method. The surface hardness in carburizing process is increased. This can be proved from Vickers Hardness Test. The Vickers Hardness (HV) number increase after carburizing process. From the reading, the edge gives smaller HV number then the center for all specimens. The smaller HV value indicates that the part is hard (Ray et. al., 2003).

1.4 RESEARCH OBJECTIVES

The objectives of this study are to:

- (i). Determine the effectiveness on hardness of carburized carbon steel by using heat treatment.
- (ii). Determine the activation energy on carburized layer.

1.5 SCOPE OF THE RESEARCH

The scopes of this study are:

- (i). Packing method is used in carburizing process.
- (ii). 3 different carburizing times are used in carburizing processes which are 8 hours, 10 hours and 12 hours.
- (iii). 3 different carburizing temperatures are used in carburizing processes which are 850°C, 900°C and 950°C.
- (iv). 3 different quenching mediums are used which are air, oil and water.
- (v). Vickers Hardness Test is used to determine the hardness of certain part on the carbon steel.
- (vi). Oil is used as quenching medium for activation energy determination.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

From the early stage of the project, various literature studies have been done. Research journal, reference books, printed or online conference article were the main source in the project guides as they contain the current knowledge on particular research. The reference sources emphasize on effect of heat treatment on surface hardness when carburizing carbon steel. Then, the value of hardness on the surface of carbon steel will be justified using Vickers Hardness Test.

2.2 HEAT TREATMENT

Heat treatment is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a particular kind of application. In general, heat treatment is the term for any process employed which changes the physical properties of steel by either heating or cooling. When properly performed, heat treating can greatly influence mechanical properties such as strength, hardness, ductility, toughness, and wear resistance (Zakharov, 1998).

2.2.1 Heat Treatment of Carbon Steels and Carbon Alloy Steels

Most carbon steels and carbon alloy steels can be heat treated for the purpose of improving mechanical properties such as hardness, tensile and yield strength. This is accomplished due to the heat treatment fundamentally altering the microstructure of the steel.

When discussing about heat treating, it must begin with the understanding of the structure and phases of metals.

The structure of steel is composed of two variables:

- (i). Grain Structure - The arrangement of atoms in a metal.
- (ii). Grain Size - The size of the individual crystals of metal. Large grain size is generally associated with low strength, hardness, and ductility.

The crystals in steel have a defined structure that is determined by the arrangement of the atoms. There are two common crystal structures in iron which are body-centered-cubic (BCC) and face-centered-cubic (FCC). When the iron is arranged in the FCC structure, it is able to absorb higher amounts of carbon than a BCC structure. It is because of the increasing in interstitial sites where carbon can sit between the iron atoms. During the alloying process elements, carbons are introduced to the steel. These alloying elements interrupt the geometry of the individual crystal structures therefore it increase the strength. Thus, the change in crystal structure is critical to successful heat treatment (Askeland, 1984).

Steel can exist in various phases which are ferrite, austenite, and cementite. These phases can be explained by referring Figure 2.2. The Y-axis (vertical) is a measurement of temperature while the X-axis (horizontal) is a measurement of the carbon content of the steel. The far left hand side of the X-axis represents the ferrite phase of steel (low carbon content) while the far right hand side represents the cementite phase of steel (high carbon content), which is also known as iron carbide. The

austenite phase is located between the dashed phase lines and occurs only above 1333 °F or 723 °C (Askeland, 1984).

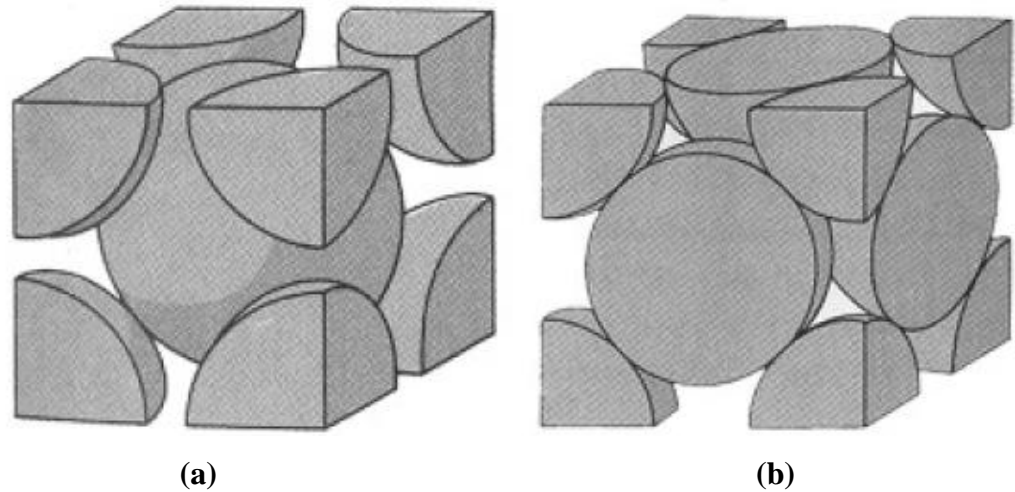


Figure 2.1: (a) Body-Centered Cubic (BCC), (b) Face-Centered Cubic (FCC)

Source: William D. Callister Jr., (1994)

The transformation from BCC to FCC provides more points (spaces between spheres) for carbon to interact with the iron.

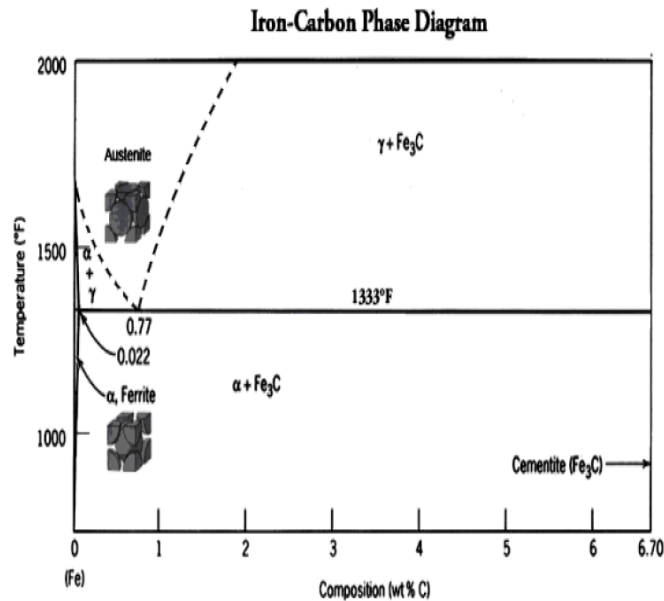


Figure 2.2: Iron-Carbon phase diagram

Source: William D. Callister Jr., (1994)

When ferrite is at room temperature, it has a BCC structure, which can only absorb a low amount of carbon. Because ferrite can only absorb a very low amount of carbon at room temperature, the un-absorbed carbon separates out of BCC structure to form carbides which join together to create small pockets of an extremely hard crystal structure within the ferrite which is cementite. However, when ferrite is heated to a temperature above the transformation line (723°C), the BCC structure changes to FCC structure known as austenite which is allowing the absorption of the carbon into the crystal structure (Parrish, 1999).

Once the steel enters the austenitic phase, all of the cementite dissolves into austenite. If the steel is allowed to cool slowly, the carbon will separate out of the ferrite as the cubic-structure reverts from face-centered back to body-centered. The islands of cementite will reform within the ferrite, and the steel will have the same properties that it did before it was heated. However, when the steel is rapidly cooled, or quenched, in a quenching medium such as oil, water, or air room temperature, the carbon does not have time to exit the cubic structure of the ferrite and it becomes trapped within it. This leads

to the formation of martensite which is the microstructure that produces the most sought after mechanical properties in steel fasteners (Parrish, 1999).

During quenching, it is impossible to cool the specimen at a uniform rate throughout. The surface will always cool more rapidly than the interior of the specimen. Therefore, the austenite will transform over a range of temperatures, yielding a possible variation of microstructure and properties depending on the position within the material. The successful heat treatment of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors (Prabudev, 1988):

- (i). The composition of the alloy
- (ii). The type and character of the quenching medium
- (iii). The size and shape of the specimen

Hardenability is the ability of steel to transform into martensite with a particular quenching treatment. This is directly affected by the alloy composition of the steel. For every different steel alloy there is a specific relationship between its mechanical properties and its cooling rate. Hardenability is not “hardness” which is a resistance to indentation but hardness measurements are utilized to determine the extent of a martensitic transformation in the interior of the material. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but also to a large degree throughout the entire interior. In other words, hardenability is a measure of the degree to which a specific alloy may be hardened (Askeland, 1984).

The newly formed martensite is considered as a grain structure but not a phase and it is very hard and brittle. Due to the brittleness inherent in martensite, steel that has been quenched from austenitizing temperatures will require tempering before it can be placed into service. Tempering involves heating the steel to a specific temperature below that of the transformation line and allowing it to cool slowly. This causes the crystal structure to relax, thereby increasing the ductility and decreasing the hardness to specified levels. The specific tempering temperature will vary based on the desired results for the steel (Parrish, 1999).

The following example will demonstrate the effectiveness of tempering:

ASTM A193 Grade B7, SAE J429 Grade 8 and ASTM A574 Socket Head Cap Screws are all made from alloy steels. In fact some alloy steel grades can be used to manufacture any of the three final products such as 4140 and 4142 alloy steel. The final mechanical properties appear in the table.

The initial heat treating process is relatively the same for all three products. The parts are heated until fully austenitized and then are quenched in oil and tempered (Chokshi, 2005).

This tempering temperature dictates the final mechanical properties. The following are the minimum tempering temperatures and its specification:

Table 2.1: Fasteners produced from AISI 4140 & 4142 Steel

Fastener	ASTM A193 B7	SAE J429 Gr. 8	ASTM A574 SHCS
Tempering Temperature	1150°F	800°F	650°F
Tensile Strength	125,000 PSI min. (2½in. and under)	150,000 PSI min.	180,000 PSI min. (through ½in.) 170,000 PSI min. (above ½in.)
Yield Strength	105,000 PSI min. (2½in. and under)	130,000 PSI min	153,000 PSI min
Proof Strength	N/A	120,000 PSI	140,000 PSI (through ½in.) 135,000 PSI (above ½in.)
Hardness	HRC 35 max.	HRC 33-39	HRC 39-45 (through ½in.) HRC 37-45 (above ½in.)

A lower tempering temperature will produce a harder and higher tensile strength part for these alloy steels. However, the lower tempering temperatures will also mean lower ductility, impact strength, operating temperature, and possibly lower fatigue life. For example, socket head cap screws and Grade 8's have an operating temperature limitation of approximately 450 °F, whereas B7 is able to function properly up to approximately 800 °F (Chokshi, 2005).

Annealing is a heat treating process used to soften previously cold-worked metal by allowing it to re-crystallize. The term annealing refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Ordinarily, annealing is carried out to relieve stresses (often introduced when cold-working the part), increase softness, ductility and toughness and produce a desired microstructure. A variety of annealing heat treatments are possible (Krauss, 1991).

Any annealing process consists of three stages:

- (i). Heating to the desired temperature
- (ii). Holding or "soaking" at that temperature
- (iii). Slowly cooling, usually to room temperature

Time is the important parameter in these procedures. Process annealing is a heat treatment that is used to negate the effects of cold work that is to soften and increase the ductility of a previously strain-hardened metal.

Stress relieving is an annealing process that is utilized when internal residual stresses develop in metal pieces in response to such things as cold working. Failure to remove these internal stresses may result in distortion and warping. The internal stresses are relieved by bond relaxation as a result of heating. A stress relief is carried out by heating the piece to a recommended temperature (approximately 165 °F or 74°C below the transformation temperature for carbon steels), holding the work piece at temperature long enough to attain a uniform temperature throughout the part, and finally cooling to

room temperature in air. Stress relieving can eliminate some internal stresses without significantly altering the structure of the material (Krauss, 1991).

Steels that have been plastically deformed consist of grains of pearlite, which are irregularly shaped and relatively large, but substantially in size. Normalizing is an annealing heat treatment used to refine the grains and produce a more uniform and desirable size distribution (Parrish, 1999).

2.2.2 Carburizing

In general, carburizing is the addition of carbon to the surface of low carbon steels at temperatures generally between 850 and 950°C (1560 and 1740°F) at austenite region that had high solubility for carbon and the stable crystal structure. Hardening is accomplished when the high-carbon surface layer is quenched to form martensite so that a high-carbon martensitic case will have good wear and fatigue resistance. Carburizing steels for case hardening usually have base-carbon contents of about 0.2%, with the carbon content of the carburized layer generally being controlled at between 0.8 and 1% C. However, surface carbon is often limited to 0.9% because too high a carbon content can result in retained austenite and brittle martensite. Carburizing process increases the grains size due to permanence for a long time in the austenitic region of the phase diagram, and makes necessary a posterior heat treatment to refine the grains. Classic quenching generates a martensitic hard but brittle material. On the other hand, intercritical quenching transforms the outward carbon-rich solid solution into martensite, while the internal microstructures present a mixture of martensite, producing a less-brittle material (Parrish, 1999).

Parts are packed in a high carbon medium such as carbon powders are heated in a furnace for 8 to 12 hours at 850°C, 900°C and 950 °C. At this temperature CO gas is produced which is a strong reducing agent. The reduction reaction occurs on the surface of the steel releasing carbon, which is then diffused into the surface due to the high temperature. When enough carbon is absorbed inside the part (based on experience and theoretical calculations based on diffusion theory), the parts are removed and can be subject to the normal hardening methods (Krauss, 1991).

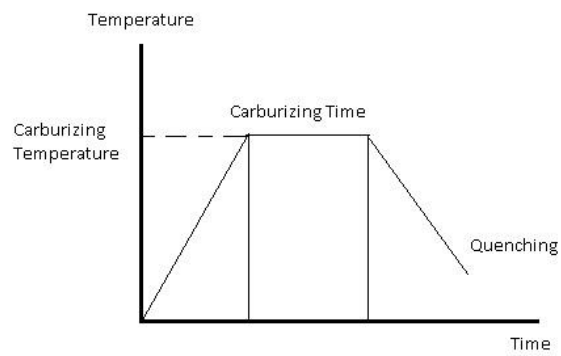


Figure 2.3: Process diagram of carburizing



Figure 2.4: Specimens container (furnace)

2.2.3 Quenching

Usually when hot steel is quenched, most of the cooling happens at the surface, as does the hardening. Different quenching media provide a variety of cooling rates.

Quenching can be done by plunging the hot steel in water. The water adjacent to the hot steel vaporizes, and there is no direct contact of the water with the steel. This slows down cooling until the bubbles break and allow water contact with the hot steel. As the water contacts and boils, a great amount of heat is removed from the steel. With good agitation, bubbles can be prevented from sticking to the steel, and thereby prevent soft spots. Water is a good rapid quenching medium, provided good agitation is done. When the fastest cooling rate is required, water solutions are used as quenching media. When suddenly quenched, the martensite is formed. This is a very strong and brittle structure. However, water is corrosive with steel, and the rapid cooling can sometimes cause distortion or cracking (Prabudev, 1988).

Oil is used when a slower cooling rate is desired. Since oil has a very high boiling point, the transition from start of martensite formation to the finish is slow and this reduces the likelihood of cracking. When slowly quenched it would form austenite and pearlite which is a partly hard and partly soft structure but oil quenching results in fumes, spills, and sometimes a fire hazard. Oils also are intermediate quenching media and they are ideal for quenching steels (Prabudev, 1988).

Quenches are usually done to room temperature. Most medium carbon steels and low alloy steels undergo transformation to 100% martensite at room temperature. When the cooling rate is extremely slow then it would be mostly pearlite which is extremely soft. However, high carbon and high alloy steels have retained austenite at room temperature. To eliminate retained austenite, the quench temperature has to be lowered. This quenching media produces the lowest cooling rate (Prabudev, 1988).